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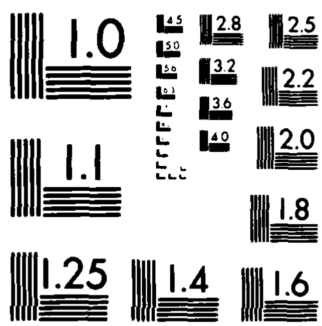

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RESEARCH ON DESIGN OF CRYOTRANSFORMERS
AND ITS PROSPECTS FOR THE FUTURE

By

W. Lech

FOREIGN TECHNOLOGY DIVISION

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RESEARCH ON DESIGN OF CRYOTRANSFORMERS AND ITS PROSPECTS FOR THE FUTURE

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Summary

Calculation results of the technical-economic parameters of large power cryotransformers with windings of pure aluminum, presented in this paper, indicate that the production of such cryotransformers could be justified and that resumption of the research work in this field would be advisable.

On the basis of significant progress in the development of new multifilament superconducting wires it was concluded that the construction of cryotransformers with superconducting windings will become feasible in the near future, and that most likely these windings will operate at the temperature of liquid hydrogen.

(Translations, Poland)

1. INTRODUCTION

Main advantages, which are expected from the introduction into use of cryotransformers instead of conventional transformers, are:

a) considerable increase of limiting unit powers,
b) severalfold decrease of dimensions and weight,
c) severalfold decrease of general losses, and specifically stray losses.

Investigations have shown that presently produced superconductors cannot be applied to the construction of windings of cryotransformers; superconductors of the 1-st kind - because of a too small value of critical field, and superconductors of the 2-nd type - because of excessive losses in alternating magnetic stray field of transformers.

In several research centers studies were also made on application of pure metals, primarily pure aluminum, for windings of cryotransformers. Although economic calculations, supplemented by results of measurements on models, were optimistic /5, 13, 15/, these studies have not led to development of the full construction of such cryotransformers. Among others, no 42
satisfactory solution was found for such an important problem as the technology of windings from thousands of parallel thin wires or tapes from aluminum.

At present time, the work on cryotransformers is conducted in only a few research centers, and is very limited in scope.

In the present paper, the author on the basis of results obtained so far is trying to answer the question what are the prospects of building cryotransformers in the future.

2. SURVEY OF RESEARCH WORK ON THE CONSTRUCTION OF CRYOTRANSFORMERS

Studies on possibility of the application of low temperatures in energetic transformers have been carried out since about 1960 /3, 4/.

The first studies, both theoretical and experimental, were concerned with cryotransformers having windings from superconductors. Models of cryotransformers of low power (about 10-20 kVA) constructed of superconductors of the 1-st kind

provided encouraging results, enabling one to assume that it would be possible to reduce severalfold the weight and losses, in relation to conventional transformers /4/. However, in view of the high cost of condensing units for cryogenic liquids, the application of low temperatures could be profitable only in transformers of high power, in which the application of superconductors of the 1-st kind is not possible because of the high value of stray fields. Subsequently built cryotransformer models with superconductors of the 2-nd kind failed to provide such encouraging results because of relatively large losses in winding in the alternating stray field /7/. These failures evoked a considerable pessimism with respect to application of superconductors in cryotransformers.

Publications appeared /6, 8, 9, 10/ which questioned the appropriateness of the construction of cryotransformers with windings of superconductors, and which postulated limit of application of superconductors of the 2-nd type only to facilities of direct current, such as electromagnets creating strong magnetic fields or exciters for turbomachines, since only with direct current the superconductors do not suffer any losses.

On the basis of the literature accessible to the author, it appears that at present there is nowhere any research work being carried out on the application of superconductors for cryotransformer windings.

Negative results of studies on application of superconductors for windings of cryotransformers induced the Alsthom Company in France to initiate investigation of the feasibility of constructing cryotransformers with windings of pure metals. The Alsthom example was followed by an American firm General Electric Company. Pure metals suitable for application are
aluminum and copper cooled with liquid hydrogen, or beryllium 43
cooled with liquid nitrogen. Since at the temperature of liquid

hydrogen the electrical properties of pure aluminum and pure copper are similar, and aluminum is cheaper, lighter and easier to purify, the research work involved nearly exclusively cryotransformers with windings of pure aluminum (Al of purity 99.999). Beryllium is very attractive because of the possibility of use of liquid nitrogen as a cooling and insulating agent, but is difficult to use because of its high cost, fragility, toxic properties and considerable difficulties in purification. Nevertheless, the Alsthom Company constructed in 1970 a small model of cryotransformer with winding of pure beryllium, but the results of measurements on this model have not been published.

The Alsthom Company built two models of cryotransformers of power about 100 and 200 kVA with windings of pure aluminum and developed the project of a large cryotransformer of power 15 MVA and potential 63 kV. The models constructed so far enabled to provide design solutions for insulating vat for windings, cryopasses, cooling system and insulating system /20/.

However, no satisfactory solution was found for the construction of windings. In the first model, windings were used of aluminum foil of thickness 50 μm and the width equal to the height of winding. However, since electrical conductivity of pure aluminum at the temperature of liquid hydrogen is about 900 times higher than conductivity of electrolytic copper at working temperature of normal transformer, the concentration of current density at the end of windings, caused by the action of the radial component of stray field, was so large that additional losses in windings were 30-times higher than the basic losses. In order to avoid the described boundary phenomena and to reduce the additional losses, the next model had winding in which particular coils in the form of tapes consisted of several hundreds of elementary parallel conductors made of

aluminum tapelets of thickness 50 μm and width 400 μm, woven
in the form of fabric based on glass fibers. In particular tapes
the elementary units were not transposed. In large cryotrans-
formers, several or over ten of such tapes would have to be
used in parallel and they should be intertransposed at the
height of the winding. Although the reduction of additional
losses was considerable, in comparison with the first model,
it was still insufficient. Further reduction of additional (stray)
losses could be gained possibly through transposition of
elementary units, in particular tapes. The technology of making
aluminum fabric is very complex and costly. Considerable
difficulties should also be expected in cryotransformers of
large power when making transposition of parallel tapes and
in connecting thousands of thin Al tapes to various types of 44
leads from the winding, for instance leads to passes or to
the tape-changer. As is seen from the above description, the
design of windings of cryotransformers, applied in the models
of the Alsthom Company, cannot be considered as a satisfactory
solution.

It seems that at present time no research work at all is carried out by the Alsthom-Savoisienne Company on cryotransformers. Undoubtedly this situation was created to some degree by failures during the development of designs for cryotransformer windings. General Electric Company has not published yet the results of their studies on cryotransformers with windings of pure aluminum. However, from some published remarks during discussion on the design of cryocables /14/ one can conclude that the work in this field is still in progress. In 1973 the All-Union Institute of Electrotechnology (VEI) in Moscow published results of investigations on the there constructed model of pure aluminum /27/. The design of

the model was very simplified. The windings were made of wire of the diameter of 2 mm. Both the winding and the core were cooled to cryogenic temperatures. At the room temperature the model had power of 800 kVA, and the ratio of total losses to the nominal power was 7.5%. On cooling the winding and the core to the temperature $14^{o}K$ the power increased 20-times, and the proportion of total losses (including losses in the condenser) to power was 18%. One can calculate that, if in the model built at VEI the core was not cooled together with the winding, and if wire of diameter 0.1 mm was used for winding, the ratio of total losses to the power would decrease to the value of about 10%. From results of the testing of a cryotransformer model made at VEI one should expect that in cryotransformers having windings of pure Al we could obtain, at the same efficiency, the power about 15-times larger than in conventional transformers.

It is expected that in the near future VEI will start extensive research work on application of pure copper, instead of pure aluminum, in models of cryotransformers. In the USSR the work is being done on development of a simple and inexpensive chemical method of copper purification. It is expected that, with application of this method, copper of purity 99.999 will be only 20% more expensive than the usual electrolytic copper.

3. SOME PROBLEMS IN DESIGN OF CRYOTRANSFORMERS WITH WINDINGS OF PURE METALS, ENCOUNTERED AT THE INSTITUTE OF ELECTROTECHNOLOGY

This section will discuss only the application of pure aluminum, since at present we have the highest experience in this field, the behavior of wires of pure aluminum in conduction of alternating current in alternating magnetic field is relatively

well known, and the technology of the purification of aluminum is mastered.

As was mentioned above, the most important and most difficult unsolved problem in the construction of cryotransformers with windings of pure Al is the design of windings. Large conductivity of pure Al at cryogenic temperatures forces one to divide coils into thousands of thin wires or parallel tapelets which should be transposed in the area of coil. As was shown by calculations and measurements conducted at the Institute of Electrotechnology (IEl) in Warsaw, the optimal dimensions of elementary conductors of pure Al for windings of cryotransformers of high power are: for round wires - diameter 100 μm; for taplets - thickness 25 to 50 μm, width 400 to 500 μm. 45

Two solutions for the lead (cable) of continuous transposition were examined at the IEl: one with application of round wires, and the second - of tapes (ribbons). The cable with continuous transposition can be used for winding of cryotransformers, and the technology of winding it (putting it on the core) will not be more complex than in conventional transformers. The cable of continuous transposition can be made in a relatively simple way using the multistage transposition. At first, conduits of continuous transposition composed of a few elementary leads are made. In the next stage, the operation of making leads of continuous transposition is repeated, and now cables made in the first stage are used as elementary units. By repeating the operation several times we can obtain one lead of continuous transposition and the required number of elementary units. For instance, after 5 stages of transposition one obtains a cable of diameter of about 37 mm and the number of parallel wires equal to 7776. One could make such a cable on the basis of glass fibre, and eventually with internal canals for cryogenic liquid. Tenacity

of such a cable at the temperature of about $20^{o}K$ is about 60 tons. The windings of cryotransformer wound with such a cable will possess a good short-circuit resistance.

The lead of diameter 37 mm can carry current of about 1600 A. With the use of such a lead the winding of upper potential of cryotransformers, even of the highest power, can be wound with a single cable. With winding having the inlet at the beginning of the column the power of such cryotransformer of potential 420 kV will be about 1200 MVA, and having the inlet in the middle of column (two parallel branches) - about 2400 MVA. The windings of lower potential will be put in the form of a multicoil screw (several parallel branches). Because of the necessity of transposition of parallel leads at the height of winding, it might be found convenient to use here leads with rectangular cross-section. Such leads of continuous transposition could be made of elementary tapelets (ribbons) of pure aluminum of thickness 50 µm and width 0.5 mm insulated with lacquer. Here we shall have also the multistage transposition, and at each stage we shall use the same technique as is used presently by some 46
producers of transformers when making leads of continuous transposition composed of a few elementary units. This number is from 3 to 31. It would be easy, therefore, to put the desired number of tapelets in the final lead.

In order to estimate advantages which could be achieved by substitution of high power transformers with cryotransformers we developed at IEl a method to calculate main dimensions and weight of cryotransformers and full losses, taking into account efficiency of condensers for cryogenic liquid. The most difficult part was to develop a formula for stray losses since, because of very high conductivity of pure aluminum

at cryogenic temperatures, these losses are affected by several factors which either do not appear at all or are of considerably less importance in windings of conventional transformers. Such factors are: strongly pronounced eddy currents and the connected with them phenomenon of skin-effect, and increase of the resistivity of leads because of dimensional effect (dissipation of conductivity electrons on walls of the leads) and phenomena of magnetoresistance (increase of resistivity in magnetic field).

All the above mentioned factors affect each other, hence development of a formula for losses in conductors has to be based on results of measurements of these losses on samples of conductors. At IEl we carried out such measurements on samples of single wires and tapelets (filaments) of pure Al as well as on samples of conductors with continuous transposition at various cross-sections of elementary units. These measurements were performed in constant and alternating magnetic fields, at temperatures of liquid helium, hydrogen and nitrogen. On the basis of measurement results and theoretical consideration we adopted formula (1) for calculation of stray losses in cryotransformers. This formula is the same as for transformers except that, to include the dimensional effect and the phenomenon of magnetoresistance, the value of resistivity $\rho_{d,H}$ was calculated from the experimental formula (2) developed at IEl:

$$P_{ob} = P_p + P_d = \frac{\rho_{d,H}\, l I_f^2\, N\, 10^2}{S_p}\left[1 + 0{,}432\, n^2 d^4 \left(\frac{L}{Lu}\, k\right)^2 \frac{10^{-16}}{\rho_{d,H}^{\,2}}\right] \qquad (1)$$

$$\rho_{d,H} = \rho_d \left\{1 + (2{,}43 - 0{,}016T)\left[1 - \frac{\rho_d 10^{12}}{0{,}35\, Br_{max}}\left(1 - e^{-0{,}35 \frac{Br_{max}}{\rho_d} 10^{-12}}\right)\right]\right\} \qquad (2)$$

The formula for $\rho_{d,H}$ also takes into account the fact that the conductors are in a winding located in the stray field, the induction of which increases linearly from 0 at the outer edge of the winding to the value of Br_{max} in the dissipation gap, and that:

$$Br_{max} = 1{,}256 \frac{\sqrt{2}\, I_f\, N\, k}{Lu} \qquad (3)$$

The resistivity of pure Al with consideration of dimensional effect ρ_d was accepted as: 47

- for round wires as the arithmetic mean of values obtained from simplified formulae of Dingle /2/ and Fuks /1/:

$$\rho_d = \frac{\rho_o}{2} \left\{ \left[1 - \frac{3}{4}\left(\frac{\lambda}{d}\right) \quad \frac{3}{8}\left(\frac{\lambda}{d}\right)^3\right]^{-1} + \left[1 + \frac{3}{4}\left(\frac{\lambda}{d}\right)\right] \right\} \qquad (4)$$

- and for tapes of thickness d according to simplified formula of Fuks:

$$\rho_d = \rho_o \left[1 + \frac{3}{8}\left(\frac{\lambda}{d}\right)\right] \qquad (5)$$

The symbols used in equations (1) to (5) are as follows:

P_{ob}, P_p, P_d - correspondingly stray, basic and additional losses in W;

$\rho_{d,H}$ - resistivity of conductor of pure Al with account of dimensional effect and phenomenon of magneto-resistance in Ω cm;

I - average coil length of winding in cm;

I_f - phase current in A;

N - number of coils in winding;

S_p - cross-section of pure Al in one coil of winding in mm^2;

n - number of elementary wires or tapes across the width of the winding;

d - diameter of elementary wire or thickness of elementary tape of pure Al in mm;

L - height of winding without insulation in cm;

L_u - height of winding with insulation in cm;

k - coefficient of Rogowski;

ρ_d - resistivity of pure Al with consideration of dimensional effect in Ω cm;

ρ_o - resistivity of pure Al in the form of massive metal in Ω cm;

T - temperature of work of winding in ^oK;

$B_{r_{max}}$ - maximal induction in dissipation gap in Gs;

λ - length of the mean free path of electrons in mm.

From measurements and calculations we obtained for pure Al (99.999) at the temperature of liquid hydrogen (20.4 ^oK):
$\rho_o = 2.38 \times 10^{-9}\ \Omega$ cm, and $\lambda = 0.02$ mm.

For economic calculations we chose a block cryotransformer with nominal voltage ratio 420/15.75 kV and power 240 MVA. This power is sufficiently large as to show in full possible advantages obtained on introduction of cryotransformers.

Liquid hydrogen was taken as cooling agent and as the agent insulating windings of cryotransformer. From the economic viewpoint the temperature of liquid hydrogen is optimal for windings of pure Al. Dielectric strength of liquid hydrogen at atmospheric pressure is about 20% higher, and at the pressure 5 atm even twice higher, than the strength of transformer oil. To be secure, we took the strength at the same as that of transformer oil.

Calculations for several variants of cryotransformers with windings of pure Al at the temperature of liquid hydrogen have shown that the optimal current density in the windings is contained in the range of 15 to 25 A/mm^2. We took the value of 20 A/mm^2. For comparison purposes we performed also calculations for the current density equal to 3.4 A/mm^2 as in conventional transformers.

Three variants used in calculations were: 48

1. With conventional system of windings (DN winding on the core, GN winding with entrance in the middle of the column on external side) and at the current density 3.4 A/mm^2.

2. As above, but at current density 20 A/mm^2.

3. With the butterfly system of windings (GN winding with entrance in the middle of the column between two halves of DN winding) and at the current density 20 A/mm^2.

The obtained ratios of losses and weights in conventional transformer to cryotransformer of the same power and nominal potential of windings are given in Table 1.

Wariant	1.	2	3
Stosunek całkowitych strat: 1 P_{tr}/P_{ktr}	3,6	3,2	3,5
Stosunek całkowutych ciężarów 2 G_{tr}/G_{ktr}	1,0	2,2	2,2

Table 1

1 - ratio of total losses
2 - ratio of total weights

As is seen from the above table, the most advantageous is the third variant, which allows one to reduce the total losses by the factor of about 3.5 and to decrease by the factor of about 2 the weight of cryotransformers in comparison with conventional transformers. Since the total losses in a block transformer 420/15.75 kV 240 MVA amount to about 1200 kW, the expected savings on losses will be about 850 kW, which corresponds to about 42,000 dollars per year. Since the cost of hydrogen condensers for cooling of cryotransformers of power 240 MVA will be about 65,000 dollars, less than two-years savings on losses will cover the cost of the condensing unit.

As is seen from the above, the reduction of losses and weights in cryotransformers with windings of pure Al cooled and insulated with liquid hydrogen in comparison with conventional transformers fully justifies continuation of research on such constructions. It does not appear either that the design of windings for such cryotransformers is not an essential obstacle in carrying out such work. Furthermore, one can visualize also possibilities of additional increase of economic advantages with the use of cryotransformers, for instance, by increasing pressure of liquid hydrogen to several atmospheres.

4. PROSPECTS OF BUILDING CRYOTRANSFORMERS 49
WITH WINDINGS OF SUPERCONDUCTORS

Until recently the superconductors of the 2-nd type were used only for windings of direct current electromagnets and for exciters of experimental turbomachines supplied with constant current. However, even in these installations at various changes of the work regime (connecting these facilities to the supply circuit and disconnecting them, load changes,

emergency conditions) there are changes of magnetic field and connected with them losses in windings which, if they exceed the permissible level, can cause transition of the winding into its normal state and lead to its damage or destruction. These considerations and the desire to apply superconducting electromagnets also to large accelerators of elementary particles, working at at impulse or slow-changing currents and fields (with frequencies of the order of 1 Hz), induced the start of intensive studies on development of superconducting cables with small losses at alternating current and with large work stability (small probability of the transition of superconductor into the normal state at normal work conditions). These studies were gradually broadened to fields and alternating currents of frequency 50 Hz and larger.

The present general opinion governing among the experts is that the coming years will see the development of superconducting leads which can be applied successfully to facilities of 50 Hz alternating current, and that only such conductors will introduce real revolution in electrotechnology. How important has become the problem of the development of superconducting cables for alternating current is witnessed by the fact that this topic was placed in 1973 as problem of the first degree of importance in works of the international organization COST (European Cooperation in the Area of Research and Technology) /28/.

The research work carried out in this field has led already in recent years to very important achievements. A theory was developed in detail for multicomponent conductors containing a large number of thin superconducting fibers frozen inside the basis of normal conducting material and suitably intertwisted, and this theory is constantly supplemented and improved /12, 16, 17/.

It seemed at first that complex construction of such conductors, postulated by the theory, would require an extremely difficult and costly technology. But even in this area the progress was very fast and at present complex conductors containing thousands of thin superconducting fibers are produced on commercial scale. As an example of the refined construction of such conductors may serve the cable developed in 1972 by the company Imperial Metal Industries /24/. The cable of diameter 1 mm contains 13,255 fibers of NbTi each of diameter 8 μm. The fibers are divided into 55 bundles, each containing 241 fibers. The bundles are separated from each other by thin walls of copper, and in the middle thickness of these walls there 50
are placed very thin barriers of high resistivity made of an alloy of copper with nickel and running in the axial direction of the cable. The cable is twisted around its axis at a suitable step of turn. This cable can carry 430 A current in constant or slowly-changing magnetic field to 50 kGs. Using transposition one can connect several conductors in parallel in the form of cables which are able to carry currents of the order of thousands of amperes. Construction of a cable with a large number of superconducting fibers made it possible to build cables for the highest currents in electrical facilities by putting small number of conductors in parallel, achieving thus their dense packing. Thus, despite the transposition, it was possible to achieve very high coefficients of filling, amounting to 50% and more. This cable was tested in the magnetic field of frequency up to 4 Hz and it showed very small losses and the critical current equal to the constant critical current, evidencing uniform distribution of the current among the singular superconducting fibers. Currently the work is being done on adaptation of the cable to the work in magnetic field of frequency 50 Hz. Among other

designs of cables used at present one should mention such ones in which single superconducting fibers are covered with a thin layer of an alloy CuNi and are set on a copper base. There are also cables in which fibers are not covered with a CuNi layer.

There are three kinds of losses suffered in alternating magnetic field by the above described cable constructions:

1) hysteresis losses in superconducting fibers,

2) eddy current losses in copper core,

3) losses of complex character caused by induction currents flowing partially along the neighboring fibers and partially across the copper base separating the fibers, forming thus closed loops.

The hysteresis losses in superconducting fibers can be lowered by reducing the diameter of fibers. Because of the better cooling of fibers one obtains then also a better work stability by elimination of the phenomenon of the so-called quantum jumps of magnetic stream in fibers. At present time there are already made on laboratory scale conductors with diameters of fibers reaching 2 μm.

The eddy current losses in copper core can be limited by reducing the percent fraction of copper in the conductor. Whereas in cables made a few years ago the volume ratio of copper to superconductor was 50:1 or more, at present this ratio is 1:1 or less. The above mentioned barriers of the CuNi alloy also reduce eddy current losses in the core.

Losses caused by induction currents constitute usually the largest part of total losses of the conductor. They can be reduced by twisting the conductor around its axis. Then, potentials induced in copper core on sections of conductor
corresponding to the neighboring steps of turn have opposite 51
directions and they cancel each other. This reduction of losses

is the greater, the smaller is the step of turn. But, because of technological reasons, the step of turn cannot be reduced at will. The use of barriers of material with large resistivity allows one to reduce the losses sufficiently with preservation of the step of turn dictated by technological reasons.

This twisting of the conductor reduces losses caused by induction currents through external alternating magnetic fields, but has no effect whatsoever on losses coming from the internal field caused by currents flowing through the fibers. For, independently of twisting, fibers located farther from the axis of conductor will be subjected to a more intense magnetic field than the fibers lying closer to the axis. In order to reduce this kind of losses, one should apply transposition of fibers inside the conductor, instead of twisting of the cable. The technology of such a transposition has not been developed yet, although research work in this area is being carried out /16/.

Superconducting cables can be applied successfully to windings of cryotransformers if losses in such cables in magnetic field to 5 kGs with frequency 50 Hz do not exceed 10 mW/cm^3 /18/. Currently, in application of cables with fibers of NbTi of diameter 2.5 μm the losses in such a field were 10 mW/cm^3 per cycle /23/. The losses were measured at the frequency less than one Hz. Taking into consideration the fact that the losses per cycle first increase with frequency (to several Hz) and then decrease and at 50 Hz amount to less than half of the value measured at frequency below 1 Hz /30/, we may conclude that it is still necessary to reduce losses by a factor of about 20 in order to be able to use superconducting cables in such facilities of alternating current as transformers. We think that this will happen already within two years in view of the fact that during the last two years

about 15-fold decrease of losses was achieved, and the fact that the work in this area continues to be carried out with increasing intensity. The main directions of this work include:

1) Development of technology allowing further reduction of the diameter of superconducting fibers in cables to values 1 μm and less,

2) Development of the technology of fiber transposition within the conductor,

3) Improvement of work stability and reduction of losses by application of special long-lasting thermal treatment /11/,

4) Application of new superconducting materials for fibers.

In this area, in some countries, for instance Japan, cables on commercial scale are already produced from such superconductors as Nb_3Sn, V_3Ga, V_3Si, Nb_3Ga and they all showed better technical parameters (transition temperature, critical field and critical current density) than cables from NbTi /25/.

In addition to studies on reduction of losses in superconducting cables and on increase of their stability, intensive work is being done on introduction of superconductors
which could be used at the temperature of liquid hydrogen 52
(20.4 ^{o}K) and higher. Already in 1967 the Bell Telephone laboratories have developed a Nb-Al-Ge superconductor with transition temperature 20.1 ^{o}K. In 1972 the RCA laboratories produced a superconductor Nb_3Ga with transition temperature 20.3 ^{o}K /26/. Finally, it was published in 1974 that Westinghouse Research Laboratories produced a superconductor Nb_3Ge with transition temperature 22.3 ^{o}K, and that superconductor of the same composition but prepared in different way by Bell Laboratories exhibited the transition temperature 23.2 ^{o}K /29/. These superconductors could already function

at the temperature of liquid hydrogen, but they are not yet produced in the form of multi-fiber cables. The application of such cables in cryotransformers would be advantageous even at present losses, because of about 30-times larger efficiency of hydrogen condensing units than helium condensers. Moreover, the use of liquid hydrogen for cooling of windings of cryotransformers would be attractive because of its considerably higher electrical strength than that of liquid helium.

One should mention here also two directions of conducted research which belong to more distant future but are extremely attractive. One of them is production of solidified hydrogen under the pressure of 2.6 megabars as superconductor. Such superconductor could work at temperature 100-200 ^{o}K /22/. The other direction of work - is production of organic superconductors with high work temperatures close to ambient temperature of environment /21/. Even a few years ago the attitude to such studies was very skeptical. However, this work has produced already some significant results. More and more often one can see in technical literature reports about reaching, for the time being on laboratory scale, pressures which do not lie far from those required for solidification of hydrogen. Lately, the news appeared that scientists at the University of Pennsylvania discovered semiconducting fluctuations in an organic material denoted by the code (TTF) (TCNO) at the temperature 66 ^{o}K [31]. All this information caused considerable stir in many research centers and activated considerably the work conducted in both these directions.

Already three years ago, at the international conference in Nice, an opinion was expressed that, in view of the progress achieved in the field of superconducting fibers, the pessimism with regard to the possibilities and desirability of building

superconducting cryotransformers has lost to a large extent its justification /18, 19/. In view of the present achievements we can conclude that this pessimism is not justified at all.

5. CONCLUSIONS

Considerations expressed in this paper lead to the following conclusions:

1. The presently produced superconducting cables 53
are not suitable yet as windings of cryotransformers. However, extensive research work that is being carried out in this area and the results obtained so far fully justify expectation that in the course of 2 the next years production will start of superconducting cables with small losses in alternating magnetic field 50 Hz, fully suitable for windings of cryotransformers. These conductors will operate probably at the temperature of liquid hydrogen, which is particularly attractive for cryotransformers in view of the large electrical strength of this medium.

2. Economic designs of cryotransformers with windings of pure aluminum or pure copper could be developed even now. The main obstacle, considered earlier to be the construction of windings, does not appear to be a big problem now. Windings prepared in a way outlined in this paper using conductors with a multi-stage transposition, or other conductors with similar construction, may provide full solution of this problem. The technology of preparing such a conductor should be considerably simpler than the technology of superconducting multifilament cables produced now on the industrial scale.

3. If it is found in the future that the most advantageous are cryotransformers with windings of superconductors, then, in the development of such cryotransformers, the results obtained in the research on design and construction of cryotransformers with winding of pure metals will be of great value. For, the majority of problems (cooling system, insulation system, vats, cryopasses) are common to both solutions of cryotransformers.

1. Fuks K.: Proceedings Cambridge Phil.Soc.1938.

2. Dingle R.B.: The electrical conductivity of thin wires. Proceedings Royal Soc. A201 1950.

3. Mc Fee R.: Superconducting power transformers-a feasibility study. Electrical Engineering 1961, 80.

4. Mc Fee R.: Application of superconductivity to the generation and distribution of electric power. Electrical Engineering 1962, 81.

5. Broniewski B., Burnier P., Carbonell E.: Quelques considérations sur l'intéret économique des cryomachines électriques.R.G.E. 1965, Nr 7-8.

6. Wilkinson K.J.R.: Prospects of employing at conductors at low temperature in power cables and in power transformers. Proceedings of IEE 1968, Nr 9.

7. Pech T.:Essais d'un transformateur à enroulements supraconducteurs de faible puissance. EGE 1967, Nr 2.

8. Reichert K.: Probleme, Möglichkeiten und Grenzen triefgekühlter Wicklungen in elektrischen Maschinen und Transformatoren. E.u.M. 1968 Nr 1.

9. Borcherds P.H. : Conductor losses in superconducting transformers. Cryogenics 1969, Nr 5.

10. Lorch H.O.: The possibility of superconducting power transformers. Cryogenics 1969,Nr 5.

11. Lange F., Verges P.: Better performance and smaller losses of superconducting selenoids by metalurgical means. Cryogenics 1969, Nr 5.

12. Barber A.C., Smith P.F.: New three-component superconducting composites. Cryogenics 1969, Nr 6.

13. Gerlach H., Müller K.: Die Anwendung der Tieftemperaturtechnik bei Transformatoren. Wissenschaftlich Mitteilungen 1969, Nr 10.

14. Granneau P. Economics of underground transmission with cryogenic cables. IEEE Trans. PAS 1970, Nr 1.

15. Lech W.: Zagadnienia techniczno-ekonomiczne w kriotransformatorach. Przegląd Elektrot. 1970, Nr 2.

16. Salmon D.R., Catterall J.A.:AC losses in composite superconducting wires .Journal of Physics D.Applied Physics 1970, Nr 7.

17. Wilson M.N., Walters C.R., Lewin J.D., Smith P.F.: Experimental and theoretical studies of filamentary superconducting composites. Basic ideas and theory. Journal of Physics D.Applied Physics 1970, Nr 11.

18. Malandain M.A.: Cryotransformateurs. Solution superaconductrice. Referat wygłoszony na międzynarodowej konferencji kriotechnicznej w Nicei w 1971 r.

19. Dosdat I., Maldy I.: Evolution des conducteurs supraconducteurs stabilisés vers les composites multifilamentaires à filaments très fins en alliage Nb Ti Referat wygłoszony na międzynarodowej konferencji kriotechnicznej w Nicei w 1971 r.

20. Lair M.Ph.: Cryotransformateurs. Solution hyperconductrice. Referat wygłoszony na międzynarodowej konferencji kriotechnicznej w Nicei w 1971 r.

21. Little W.A.: Higher temperatures, Theoretical models. Physica. Europhysics Journal 1971, vol 55.

22. Schneider T. Stoll E.: Metallic hydrogen II high-temperature superconductiity Physica. Europhysics Journal 1971, vol 55.

23. Mailfert A., Pech T.: Losses of twisted superconducting composite conductors. Proceedings of the Fourth International Cryogenic Engineering Conference.Eindhoven 24/26 May 1972.

24. Popley R.A., Sambrook D.J., Walters C.R., Wilson M.N.: A new 13255 filament superconducting composite. Proceedings of the Fourth International Cryogenic Engineering Conference. Eindhoven 24/26 May 1972.

25. Hulm J.K. Conference Report. Highlights of the 1972 Applied Superconductivity Conference. Cryogenics 1972. Nr 6.

26. Research News. Nb_3Ga superconducts at 20,3°K. Cryogenics 1972, Nr 6.

27. Jełagin W.N., Karapaziuk W.L., Truchin E.L. i in.: Ekspierimentalnoe issledowanie kriogennowo transformatora małoj moszcznosci. Elektrotiechnika 1973, Nr 3.

28. Schaetti N.: Die Supraleitung. Ihre Anwendung in der Elektrotechnik. Bull S. E.V. 1973 Nr 17.

29. Research News.: Record transition temperatures for superconductors. Cryogenics 1974, Nr 1.

30. Kwasnitza K., Horvath I.: Measurement of ac losses in multifilament superconducting wires at frequencies between 1 and 100 Hz. Cryogenics 1974, Nr 2.

31. Research News. Superconducting fluctuations in organic materials. Cryogenisc 1974, Nr 4.

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